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Offshore helicopter routing in a hub and spoke fashion: minimizing expected number of fatalities

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Abstract

Helicopters are often used for transportation of workers to and from offshore installations. Flying helicopter is a risky business and is often considered as one of the main risk factors in this industry. The present paper is dealing with different routing policies for minimizing the expected number of fatalities where the transportation is performed in a hub and spoke fashion from a land based heliport to a set of offshore installations either using the heliport as a hub or using one or more offshore installations as hubs. Some theoretical results are offered as well as an exact model when one operates with more than one offshore hub.

Keywords: routing; hub and spoke; safety; helicopters; offshore petroleum's industry

1. Introduction

In the offshore oil and gas industry oil companies most often use helicopters in order to bring the crews working on the offshore installations out to the platforms and back again. This is a fairly quick and efficient way to serve these installations both with the people who operate them on a daily base, but also bringing maintenance people and experts to platforms for shorter or longer times, performing special tasks. However, this type of transportation is often perceived by the workers to be uncomfortable and unpleasant due to the noise of the helicopter and turbulence that can be violent when the weather is bad. In addition, flying helicopter is a fairly risky activity and much more risky than flying an ordinary plane or driving a car. For more details about this see in[1,2,3,4,5,6]. The risk during landings and take-offs are considered to be substantially larger than during cruising between the heliport (HP) and

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the installations or between the installations. This is especially true when it comes to landings or take-offs on the platforms, where the helicopter deck is narrow with a lot of equipment like cranes and containers create big challenges for the pilots. For statistics, describing the risk of flying helicopters in different countries, see[7,12]. In the scenarios treated by[1,2,3,4] risks connected with both take offs/landings as well as cruising risks are considered simultaneously and different routing policies are considered in order to minimize the expected number of fatalities. In the present paper the same is done, but in contrast to[1,2,3,4] , we consider hub and spoke systems.

An accident is called fatal when one or more people die or is seriously injured in an accident. Routing of helicopters can neither decrease nor increase the probability that an unwanted fatality takes place. But – as described in the articles mentioned above – by applying special routing policies the expected number of fatalities can be reduced. However, this will often lead to increased costs/increased number of flying hours. In[1,2,3,4] several different routing policies are considered. Basically all of them are variations of classical vehicle routing problems with pick-up and delivery demands under capacity restrictions on the helicopters. All helicopters start from a HP serving a subset of the offshore installations and return to the HP with the people that have been picked up from the installations. In many cases the helicopters perform a flight from the HP to a single customer, deliver whatever number of people and picks up those who are going back. In other cases the routes can be small cycles visiting two to three installations before returning to the HP. All the installations in such routes are usually visited exactly once, that is, the pick-up and delivery services are performed simultaneously. In some cases an installations may be visited twice. In such a case the out-bound passengers are delivered on the first visit and the home-bound passengers are picked up on the second visit.

In the present paper we will consider some different options. The first option is to perform the required service in a hub and spoke fashion from the HP. That is, each and every installation (customer node) is served exclusively by a helicopter. This solution can be very expensive and time consuming, but it is proved in[1,2,3,4] that this solution outperforms any other routing policies treated in the traditional VRPPD way, whether the service is simultaneously or non-simultaneously performed given that the objective is to minimize the expected number of fatalities.

The new and different approach is to select one or more of the offshore installations as hubs. The out-bound passengers are taken from the HP to one of these offshore hubs and then brought to their final destinations from this hub by exclusive flights to each of the spoke nodes that are assigned to the chosen offshore hub. The home-bound passengers are brought back to the offshore hub and will wait there until all the spoke nodes are visited. Then finally all the home-bound passengers will be brought back together to the HP.

The rest of this paper is organized as follows: In section 2 using the HP as a hub is compared to a situation where a single installation is chosen as an offshore hub. In section 3, two or more offshore installations are chosen as a hub and a mathematical model is offered to decide which nodes to select as hubs and how to assign the remaining nodes to the hubs.

2. Two different single hub and spoke solutions

In[1,2,3,4] it is shown that using a single helicopter performing the services in a hub and spoke fashion outperformance the results compared to a Hamiltonian cycle. In the present paper we will compare two hub and spoke situations. The first will be the situation where the HP is used as the hub, that is, all the installations will be served directly from the HP. In the second situation one of the installations will be chosen as a hub. All passengers will be brought from the HP to this installation and from this node be brought by single flights to their final destinations where the pick-up passengers are collected and brought back to the hub. When all installations have been visited, all the pick-up passengers will be brought back to the HP with the helicopter, see Fig. 1 below. The rectangle symbolizes the HP and the circles the customer nodes/ installations.

Notation: We will denote the nodes by $i = 0,1,2,\ldots,n$ where 0 denotes the HP and the other are the customers nodes. Each node has a certain delivery demand d_i , and a certain pick up demand p_i , such that $d_i + p_i > 0$. We will assume that each of the nodes that are not a hub will be visited only once, hence, for customer nodes not chosen to be a hub, the service will be simultaneous. We will let $\sum_{i=1}^{n} d_i = D$ and $\sum_{i=1}^{n} p_i = P$. Further, we let Q denote the capacity of the helicopter and assume that $D \le Q$ and $P \le Q$.

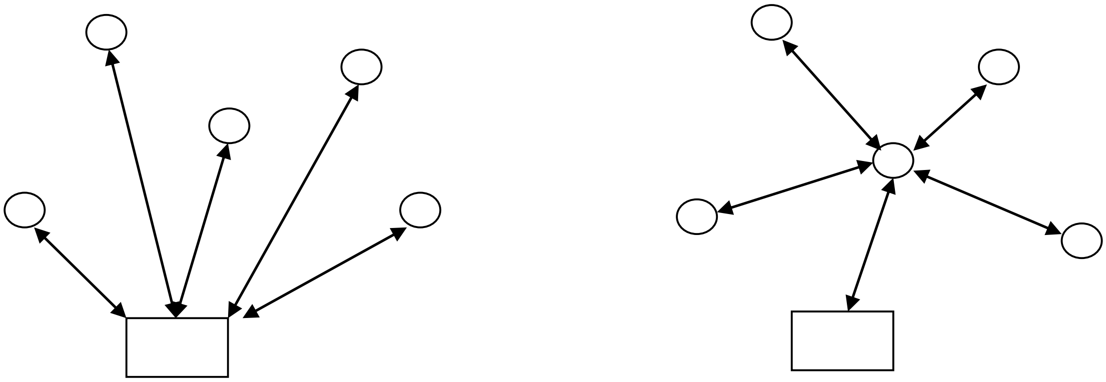

Fig. 1. (a) first picture; (b) second picture. Two single hub solutions.

As mentioned in the introduction, choosing different routings for the helicopter(s) can only influence the expected number of fatalities, not the probabilities that some accident happens due to bad weather, mistakes made by the pilots or problems based on some technology break down. Until further notice, we will not consider the probabilities for fatal accidents neither during cruising time nor during landings or take offs. These probabilities will be different. It may even happen that there are different probabilities for landing and take offs on different installations due to the space on the platform deck and other equipment close to the helicopter deck. There will also be different probabilities concerning the installations and the land based HP. Hence, there will be only three concepts that will be of interest.

Let C=[c_{ij}] $_{(n+1)x(n+1)}$ the cost matrix of travelling from node i to node j and $c_{ii} = 0,\ \forall i, i = 0,1,2\ldots,n$ .The costs can be given as a distance, a certain amount of money or time, but in order to avoid confusion we will interpret these costs as distances. Further, we let $R_i(C) = \sum_{j=0}^{n} c_{i,j}$, that is the row sums in the cost matrix C, and $R_i(C \setminus \{0\}) = \sum_{j=1}^{n} c_{ij}$, which is the row sums for the matrix C restricted to the customer nodes.

Costs

C_{HP}= $2R_0$ is the cost of using helicopter(s) when the services are performed from the HP in a hub and spoke fashion (fig.1a)

$C_{i*} = 2c_{0,i*} + 2R_{i*}(C \setminus \{0\}) = 2R_{i*}$ is the cost of using helicopter(s) when the services are performed from installation $i*$, bringing all out-bond passengers from the HP to installation $i*$, $i*$ acting as a hub for the other installations, collecting all the pick-up demands here before bringing them back to the HP via the hub (Fig.1b).

Number of passengers taking part in landings and take offs.

$PL_{HP} = \sum_{i=1}^{n} (d_i + p_i) = D + P$ is the number of passengers taking part in landings when the HP is used as a hub.

$PL_{i*} = (D+P) + (D+P) - (d_{i*} + p_{i*}) = 2(D+P) - (d_{i*} + p_{i*})$ is the number of passengers taking part in landings when installation $i*$ is used as a hub.

Number of passengers on board the helicopter multiplied with the flying distance they stay on board.

$PC_{HP}=\sum_{j=1}^{n}c_{0j}\left(d_j+p_j\right)$ is the number of passengers multiplied with the flying distance they stay on board when the HP is used as a hub.

$PC_{i*}=(D+P)c_{0,i*}+\sum_{j=1}^{n}\left(d_j+p_j\right)c_{i*,j}$ is the number of passengers multiplied with the flying time they stay on board when installation $i*$ is used as a hub.

Note that the two last definitions can be interpreted as transportation work, performed by the helicopter and will be referred to as transportation work below. From the formulas above the following expressions are straightforward, starting with the situation that the HP is the hub. Inequality (1) gives simple upper and lower bounds on the transportation work performed by the helicopter:

$$\min_j\left\{d_j+p_j\right\}R_0\le PC_{HP}\le\max_j\left\{d_j+p_j\right\}R_0 \tag{1}$$

Combining (1) with the cost/distances travelled from the HP, we get the following inequalities:

$$\frac{1}{2}\min_j\left\{d_j+p_j\right\}\le\frac{PC_{HP}}{C_{HP}}\le\frac{1}{2}\max_j\left\{d_j+p_j\right\} \tag{2}$$

giving upper and lower bounds for the fraction of the transportation work relative to the flied distance.
From the formula for transportation work from the HP we can obtain the inequalities in (3)

$$\min_j\left\{c_{0j}\right\}\left(D+P\right)\le PC_{HP}\le\max_j\left\{c_{0j}\right\}\left(D+P\right) \tag{3}$$

which in combination with the formula for the passenger landings from HP can be transformed to

$$\min_j\left\{c_{0j}\right\}\le\frac{PC_{HP}}{PL_{HP}}\le\max_j\left\{c_{0j}\right\} \tag{4}$$

Inequality (4) gives an upper and lower bound for the fraction of the transportation work relative to the number of passengers taking part in landings and take-offs. If the offshore nodes are fairly equidistant from the HP, the upper and lower bound will be close to each other. The formula for the transportation work for an offshore hub can easily be reformulated into (5), giving upper and lower bounds for the transportation work performed from the chosen hub $i*$ to the other installations.

$$(D+P)c_{0,i*}+\min_j\left\{d_j+p_j\right\}R_{i*}(C\setminus\{0\})\le PC_{i*}\le(D+P)c_{0,i*}+\max_j\left\{d_j+p_j\right\}R_{i*}(C\setminus\{0\}) \tag{5}$$

Further, inequality (5) shows that if one wants to have as small upper bound as possible, the hub should be chosen such that the sum of the distances from the hub to the other offshore installations should be as small as possible. A reasonable interpretation of this will be to choose the hub among the installations located in the middle of all the offshore installations. On the other hand, this upper bound will increase if the chosen hub is far from the HP.

Lemma 1

If one chooses a customer node as a hub, the number of passenger landings will be minimized by choosing a node

k such that $d_k + p_k = \max_j \{d_j + p_j\}$.

Proof:

The result follows directly from the formula of passenger landings when using an offshore node as a hub.

Hence, it is straight forward to find the best offshore hub if we restrict ourselves only to look at the number of passenger landings.

Above we have looked at the two situations – HP as a hub and an offshore installation as a hub – separately. Below two lemmas are given saying something about the relationship between the two choices.

Lemma 2

If the triangle inequality holds for the cost matrix C, the following inequality holds for any choice k as a hub among the customer nodes:

$$PC_k \geq PC_{HP} \text{ and } PL_i > PL_{HP}.$$

Proof:

Regarding the first inequality we have:

$$PC_k = (D+P)c_{0,k} + \sum_{j=1}^{n} (d_j + p_j) c_{k,j} = \sum_{k=1}^{n} (d_k + p_k) c_{0.k} + \sum_{j=1}^{n} (d_j + p_j) c_{kj} =$$

$$\sum_{j=1}^{n} (d_j + p_j)(c_{0k} + c_{kj}) \geq \sum_{j=1}^{n} (d_j + p_j) c_{0j} = PC_{HP}.$$

The second inequality follows immediately by comparing the number of passenger landings for the two situations.

Hence, as a consequence, choosing the HP as a hub will always outperform choosing a customer node as a hub in terms of number of passenger landings and transportation work.

Above we have discussed two of three concepts, namely the number of passenger landings and the transportation work. The third concept is the distance the helicopter has to fly or the time it has to be in the air. Comparing the flight hours when the HP is used as a hub with the flight hours used when a customer node is used as a hub is difficult and will rely heavily on how the customer nodes and the HP is located relatively to each other. In offshore oil and gas activity the HP is often located close to the coast with all the installations out in the sea - broadly speaking – in the same direction. Hence, in this case the flight hours needed to serve the installations using the HP as hub often will lead to a large number of flying hours and much bigger than if some centrally located installation is used as a hub. Actually the node with the smallest row sum in the cost matrix C will be the optimal location for the hub if one wants to minimize the number of flying hours. This will not necessarily be the HP but could often be an installation out in the sea. Hence, when it comes to costs it may be beneficial to operate with a hub that is not the HP. Further, it may happen that some of the installations are located so far from the HP that it could be difficult to reach then directly from the HP without refueling the helicopter. It may also be convenient to have an offshore hub for a person going from one installation to another via this hub, instead of having to return to the HP to be brought out to the second installation from the HP.

Algorithm for finding the best offshore hub –single hub case.

Let π_L and π_C be the probabilities for a fatal accident during landings/take offs and cruising, respectively. We want to minimize the following objective, the total probability (TP) of having a fatal accident, TP.

$$TP = \pi_L PL_i + \pi_C PC_i = \pi_L \left(2(D+P) - (d_i + p_i)\right) + \pi_C \left((D+P)c_{0,i} + \sum_{j=1}^{n} (d_j + p_j) c_{i,j} \right) \tag{6}$$

Since we have n offshore installations, we can calculate (6) for each of them and choose the one with the smallest probability. Hence, the algorithm is polynomial with complexity. The optimal solution will of course depend partly on the demand pattern. As a consequence the offshore hub can change form one time horizon to the next. It may also happen that some of the offshore installations are not suited as a hub due to different reasons like special activities going on making hindrances for frequent landing and take offs, that the number of people on board the platform is too big compared to the capacity of the life boats or that a platform does not have equipment for re-fueling the helicopter. Of course such platforms have to be excluded from the calculations above, even if they otherwise are good candidates for a temporarily hub.

A single helicopter performing all the visits may run out of time during the given time horizon. If this is the case we need two or more helicopters to perform the services. This situation will be treated in the next section.

3. Multiple helicopters and multiple hubs among the customer nodes

In this section we will assume that we have two or more helicopters performing the pick-up and delivery service. We will assume that the service is performed simultaneously, that is, every node is visited one and only one time by a helicopter except the chosen hubs which of course have to be visited several times.

There will be three basically different situations:

1. All the helicopters use the HP as a hub, visiting disjunctive sub-sets of the customers.
2. Each helicopter has different offshore installation as its hub, starting from the HP with the delivery demands that belong to their specific disjunctive sub-sets of the customers in a hub and spoke fashion and bringing all the pick-up demands back to the HP.
3. A subset of the helicopters is using the HP as a hub and the remaining subset of the helicopters is using specific customer nodes as their hubs.

3.1All the helicopters are using the HP as a hub. In this case the flying distance, the number of passenger landings and the transportation work will be the same as in the single helicopter case. The flying distance or the time used to serve the offshore installation may become large, but using the HP as a hub having several helicopters will still outperform case 2 and 3 when it comes to passenger landings and transportation work. Using more than one helicopter one tacitly assumes that there is some restriction on time (or distance) that each helicopter can use to perform its service. If this time restriction is small, then one may have to use n helicopters, one for each of the offshore installations. If it is somewhat bigger a helicopter can serve more than one installation during the given time horizon. It will be a separate problem to find which installations to combine such that the number of necessary helicopters will be minimized.

Using several helicopters each choosing a customer node as a hub

Assume that we have $k=1,2,\ldots,m$ helicopters. Let i_k be the customer node chosen as the hub for helicopter number k. Let N_k be a subset of $N\setminus\{0\}$ such that $N_k \cap N_l = \emptyset, k \neq l$ and $N_1 \cup N_2 \cup \ldots \cup N_m = N\setminus\{0\}$. N_k denotes the customer nodes that is served by helicopter k, starting from the HP with all the passengers that are going to the nodes in N_k , then using node k as a hub bringing all the delivery demands from k to the other nodes in N_k and bringing the pick-up demands back to k and bringing all pick up demands back to the HP.

The different concepts for this situation are given in the expressions (7) – (9) below.

$$C = \sum_{k=1}^{m} C_{i_k} = 2\sum_{k=1}^{m} c_{0,i_k} + 2\sum_{k=1}^{m}\sum_{j\in N_k} c_{i_k,j} \tag{7}$$

$$PL = \sum_{k=1}^{m} PL_{i_k} = \sum_{k=1}^{m}\sum_{s\in N_k}(d_s + p_s) + \sum_{k=1}^{m}\sum_{\substack{j\in N_k \\ j\neq i_k}}(d_j + p_j) = \tag{8}$$

$$D + P + (D+P) - \sum_{k=1}^{m}\left(d_{i_k} + p_{i_k}\right) = 2(D+P) - \sum_{k=1}^{m}\left(d_{i_k} + p_{i_k}\right)$$

$$PC = \sum_{k=1}^{m} \sum_{s \in N_k} (d_s + p_s) c_{0,i_k} + \sum_{k=1}^{m} \sum_{\substack{s \in N_k \\ s \neq i_k}} (d_s + p_s) c_{i_k,s} \tag{9}$$

Now, assuming that one wants two or more offshore hubs, the following two decisions have to be made under the restriction of not violating the helicopters capacities:

1. Which installations to choose as offshore hubs?
2. Which installations should be assigned to which hub?

We will assume that the demands during the time horizon are given as D and P, but are so big that they cannot be handled by a single helicopter. Further, it is assumed that the number of helicopters is the smallest integer m, such that, where Q is the capacity for a single helicopter, all helicopters are uniform.

Lemma 4

For a given choice of m offshore installations, the number of passenger landings will be independent of the way the spoke nodes are assigned to the offshore hubs.

Proof:
Follows directly by (8).

An exact model for deciding which offshore installation that should be chosen as hubs, when the number of helicopters, that is the number of offshore hubs, is given.

In addition to the notation already given the following notation will be used:

m is a parameter denoting the number of helicopters.

Variables:

PL the number of passenger landings
PC the transportation work

$U_i = 1$ if node i is chosen as an offshore hub and 0 otherwise, $i = 1,2,\ldots,n$
$W_{ik} = 1$ if node k is served from the offshore hub i, and 0 otherwise, $i, k = 1,2,\ldots,n$

The model

$$\min(\pi_L PL + \pi_C PC)$$

Subject to

$$PL = 2(D+P) - \sum_{i=1}^{n} (d_i + p_i) U_i \tag{10}$$

$$PC = \sum_{i=1}^{n} \sum_{k=1}^{n} c_{0,i} (d_i + p_i) W_{ik} + \sum_{i=1}^{n} \sum_{k=1}^{n} c_{ik} (d_i + p_i) W_{ik} \tag{11}$$

$$\sum_{i=1}^{n} U_i = m \tag{12}$$

$$W_{ik} \leq U_i, \forall i, k = 1,2,\ldots,n \tag{13}$$

$$\sum_{\substack{k=1 \\ k \neq i}}^{n} d_k W_{ik} + d_i U_i \leq Q, \forall i = 1,2,..n \tag{14}$$

$$\sum_{\substack{k=1 \\ k \neq i}}^{n} p_k W_{ik} + p_i U_i \leq Q, \forall i = 1,2,..n \tag{15}$$

$$\sum_{i=1}^{n} \sum_{\substack{k=1 \\ k \neq i}}^{n} d_k W_{ik} + d_i U_i = D \tag{16}$$

$$\sum_{i=1}^{n} \sum_{\substack{k=1 \\ k \neq i}}^{n} p_k W_{ik} + p_i U_i = P \tag{17}$$

The objective minimizes the expected number of fatalities depending on the number of passenger landings and cruising distance multiplied with the number of passenger on board. (10) and (11) give the number of passenger landings and transportation work, respectively. Constraint (12) specifies the number of helicopters. Constraint (13) says that if an offshore installation is not selected as a hub, no transportation can take place from this hub to any of the other offshore installations. Constraints (14) and (15) ensure that the capacities of the helicopters are not violated, neither for the out-bound nor the homebound demands, respectively. Finally, Constraints (16) and (17) ensure that all the necessary transportation take place, both for the out-bound and the home bound traffic, respectively.

The above model is a 0/1 program. As the number of installations increases, the number of 0/1 variables will also increase and solving the model to optimality may become difficult or take too long time, even if the model is treated as a tactical or strategic tool. On the other hand, the number of installations assigned or served from a specific HP, will in many real life situations not be very big and the model can be solved to optimality. If the model is used on a day to day basis where the hubs can be changed from one day to the next, time for solving the model can be limited, and a quicker way to find feasible solutions may be necessary. It is then necessary to rely on some heuristics to find feasible solutions. But finding and discussing such heuristics are beyond the scope of this paper.

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